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Triple Recycling Channel Strategies for Remanufacturing of Construction Machinery in a Retailer-Dominated Closed-Loop Supply Chain

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Abstract: Firms engaged in remanufacturing activities generally adopt more than one recycling channel to collect more used products and gain more profits. This paper explores the optimal strategies for a retailer-dominated closed-loop supply chain (CLSC) with a triple recycling channel in the construction machinery remanufacturing context. In this special system, the retailer is the leader and authorized by the original equipment manufacturer (OEM) to remanufacture. Moreover, the OEM, the retailer, and the secondary market all take part in the used products collection activities. Considering the differentiation of the OEM, the retailer, and the secondary market in collecting the used construction machinery, a mathematical model of the CLSC system based on reasonable assumptions is built, the closed-form optimal pricing decisions are derived, and the optimal collection efforts allocation strategies are explored within the framework of the game theory. In addition, the impacts of the reverse logistics cost coefficient, the competing coefficient, and the buy-back price coefficient on the supply chain performance are elaborately analyzed. These achievements provide decision makers with managerial insights and offer efficient guidelines for the construction machinery remanufacturing firms to solve similar puzzles.

Keywords: supply chain management; retailer-dominated; triple recycling channel; reverse logistics; construction machinery remanufacturing

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1. Introduction

In light of the financial and environmental benefits in product remanufacturing, the research on closed-loop supply chain (CLSC) has gained significant momentum in academia and industry over the last few years [1,2]. CLSCs not only involve the forward flow of new products from upstream suppliers to the final users, but also include the reverse flow of used products back to the remanufacturers [3–5]. With infrastructure construction roaring ahead in many developing countries, for example, China, the demand for various construction machinery is booming, thus, a gargantuan market has been creating a huge business opportunity for remanufacturing activities. In 2005, Lei Shing Hong, the first sole dealer of Caterpillar, established Yangzhou Used Equipment Center and started to refurbish and remanufacture the equipment produced by Caterpillar [6]. As well, in 2008, Sevalo Construction Machinery Group Co., Ltd., the leading green supply chain facilitator of construction machinery in China, cooperated with Doosan Group to develop in remanufacturing technologies and reverse logistics [7]. Despite of the lucrative prospects relating to remanufacturing, most of the original equipment manufacturers (OEMs) devote themselves to the development and research of the manufacturing process to avoid potential economic risk [8]. Meanwhile, some regional retailers with perfect forward channels have advantages over the traditional OEMs to dominate the distributing business, after-sales service and remanufacturing business in the CLSC. As pointed out by Karakayali et al. [9], the agent that provided the collection or the remanufacturing processing service was likely to derive the decision making in the supply chain. Consequently, the leadership power of the channel gradually turns to the retailer in many fields.

As a matter of fact, CLSCs mainly focus on product returns [10]; accordingly, the suitable design of the reverse channel is quite essential. In general, the remanufacturers can collect the used products through the following three options, namely, collecting from the manufacturer, collecting from the retailer through the selling network, and entrusting the activities to the secondary market (third party) [11]. To efficiently collect enough quantities of end-of-life products from all kinds of customers, many remanufacturing firms have adopted more than one recycling channel. For instance, ReCellular Inc., the largest recycler and reseller of mobile phones in the world, collects the used phones from both the regional agents and the secondary market [12,13]. Analogously, to collect enough used construction equipment, Wuhan Sevalo Construction Machinery Remanufacturing Co., Ltd. not only offers "cash for clunkers", "used for brand new" and "used for remanufactured" programs to the end users for the product returns, but also collects the used products from the local secondhand market and some OEMs to achieve economies of scale in their collection activities. Hence, for the remanufacturer that adopts a triple recycling channel, some theoretical and managerial questions, such as how to allocate the collection efforts to the agents in the CLSC, and how to make optimal pricing decision to achieve substantial profits, are major issues to be addressed.

In order to solve aforementioned issues, this paper models a retailer-dominated CLSC system consisting of an OEM, a retailer (who also acts as the remanufacturer) and a secondary market, in which all these three members collect the used products in the reverse channel for the remanufacturer. In general, the contribution of this paper can be summarized as follows. Firstly, we deduce the closed-form best pricing and collecting decisions, and reveal the key factors which determine the optimal combination mode of the triple recycling channel based on the framework of the game theory. Secondly, by conducting a numerical study, we characterize the key theoretical results with elaborate illustrations, and provide the decision makers with managerial insights on how to make policies when facing with a triple recycling channel. To the best of our knowledge, this paper is the first one that thoroughly investigates recycling channel strategies in the retailer-dominated CLSC with triple recycling channel in the remanufacturing context.

The rest of this paper is organized as follows: Section 2 summarizes the recent literature associated with this paper. Section 3 models a retailer-dominated CLSC system with a triple recycling channel motivated by a supply chain managerial example in the construction machinery industry. Section 4 explores the optimal strategies of the remanufacturer on the allocation of the collection efforts to the OEM, the retailer and the secondary market in the retailer-dominated CLSC. Section 5 conducts the performance analysis, and provides manage insights for policymaking. Section 6 provides concluding remarks and investigates possible directions for the future.

2. Literature Review

Recently, copious literature about CLSCs have been published, we refer the readers to the books of Ferguson and Souza [5] for complete reviews of this area. In these literatures, various aspects of the CLSC for products remanufacturing has been elaborately explored, and management insights are provided to the decision makers facing with similar circumstance. For example, Vlachos et al. [14] and Tagaras et al. [15,16] studied the strategic issue of the capacity planning in CLSC with remanufacturing, and developed the system dynamics methodology to evaluate the policies of the decision makers. Chung et al. [17] proposed a multi-echelon inventory system with remanufacturing capability, and found that the joint profit of the CLSC would significantly increase when the integrated policy is adopted. Chen and Chang [18] concentrated on the co-opetitive strategy of the OEM, and investigated under what conditions an OEM would participate in remanufacturing. In addition, Tagaras and Zikopoulos [19] examined the feasibility of establishing a sorting procedure in a remanufacturing

CLSC, and analyzed the optimal replenishment policy. Different form the above-mentioned works, our research mainly focuses on the front end of reverse supply chain activities [20], and it belongs to the aspects of recycling channel choice problem in the CLSC with remanufacturing. Following the systematic literature review process conducted by recent research [21–24], we review the literature related to issue of recycling channel choice in CLCS for products remanufacturing.

The works of Savaskan et al. [11] laid the basis on recycling channel choice. In them, they investigated three different recycling channels, and made comparative analysis of the optimal retail prices, collection rates and the profits of the manufacturer within the framework of game theory. They concluded that the agent, who was closer to the customer, was the best choice. Taking into account the different collection strategies adopted by the collection agents, Atasu et al. [25] further extended the work of Savaskan et al. [11] to explore how the different collection cost structure influenced the single recycling channel decision. These pioneering works have laid the foundation for the study on choosing the applicable single recycling channel under different situations, and provided insights to later researchers. For example, Shi et al. [26] further extended this research to consider the collection responsibility sharing mechanism of the collection agents, and they found that the collection managed by the secondary market was the least efficient one, and the decision on manufacturer collection and retailer collection was determined by the value of the cost parameter for the OEM. Furthermore, Xu and Liu [27] addressed the reference price effect on the performances across these three decentralized recycling channels, and examined the impact of the reference price parameter on the optimal strategies. Their research showed that high reference price parameter benefited the secondary market, and the scenario without reference price effect was generally superior to that one with reference price effect. Considering the short life cycle and the volatile demand of high-tech products, Chuang et al. [3] explored a three-echelon CLSC and analyzed the optimal strategies in constructing the channel structure. The above works [3,11,25–27], with respect to the issues on product return management, have provided methods for choosing the optimal recycling channel (manufacturer collection vs. retailer collection vs. the secondary market collection) befitting to the remanufacturer under different circumstance, though most of them talked about this issue within OEM-dominated CLSCs.

Besides the channel structure decision, several authors also have made efforts to explore the pricing decision and the collection decision in CLSCs. For example, Östlin et al. [28] identified seven different types of CLSC relationship for the remanufacturer to collect cores. El Korchi and Millet [8] proposed the alternative channel structures with less environmental impact and higher economic benefits among 18 generic structures. Das and Dutta [29] considered the product remanufacturing, the component reuse and the remanufacturing policies in a system dynamics framework, and examined the method to reduce the order variance and bullwhip effects. Choi et al. [30] analyzed the impact of different channel leadership on the performance of the CLSC, and concluded that the retailer-led model is the most effective one. Shulman et al. [31] addressed the influence of the channel structure on the optimal return policy by employing an analytical model. However, these works only consider the scenario that only a single agent takes the used product collection efforts, which may restrict the application of them in a certain degree.

To fill in this gap, some researchers have already conducted studies on product returns management of CLSCs with more than one recycling channel lately. Jiang et al. [32] explored the pricing decisions in a dual-channel that both the traditional retailer channel and the emerging internet channel are adopted, and they designed a learning search algorithm to solve the proposed model. In addition, Senthil et al. [33] adopted a hybrid decision-making methodology to evaluate the most efficient reverse logistics operating channel among manufacturer collection (MC), third party collection (TPC) and joint collection. Huang et al. [34] further investigated the optimal strategies of a manufacturer oriented CLSC with dual recycling channel, in which the collection responsibility was taken by the retailer and the secondary market, and they compared the channel performance in their work with the one in the work of Savaskan et al. [11]. In addition, they derived the parameter scope where the dual recycling channel was the better choice and gave macro-control policymaking suggestions based on exhaustive numerical analysis. Hong et al. [12] explored three hybrid collection channel structures, which were the OEM and the retailer jointly managing the recycling channel, the OEM and the secondary market jointly managing the recycling channel, and the retailer and the secondary market jointly managing the recycling channel. They concluded that the recycling channel that jointly managed by the OEM and the retailer was the best one, and they also designed the corresponding channel coordination mechanism to improve the channel performance. Yi et al. [35] further considered the collection allocation mechanism in a retailer oriented CLSC with dual recycling channel, and they concluded that the optimal allocation of the collection efforts to the retailer and the third party is determined by the relationship of the reverse logistics cost coefficients. A summary of the recent papers on recycling channel structure design in CLSC is presented in Table 1.

Table 1. Summary of papers on recycling channel structure design in a closed-loop supply chain (CLSC).

Reference	Problem Type	Solution Method	Recycling Channel
Savaskan et al., 2004 [11]	Manufacturer collection (MC) vs. retailer collection (RC) vs. secondary market collection (SMC)	Game theory	Single, manufacturer-dominated
Atasu et al., 2013 [20]	MC vs. RC vs. SMC under different collection cost structure	Game theory	Single, manufacturer-dominated
Shi et al., 2013 [26]	MC vs. RC vs. SMC under collection responsibility sharing mechanism	Game theory	Single, manufacturer-dominated
Xu and Liu, 2014 [27]	MC vs. RC vs. SMC under the effect of reference price	Game theory	Single, manufacturer-dominated
Chuang et al., 2014 [3]	MC vs. RC vs. SMC for high-tech product under different collection cost structure	Game theory	Single, manufacturer-dominated
Choi et al., 2013 [30]	Third party manages the collection activities	Game theory	Single, manufacturer-dominated vs. Retailer-dominated vs. third-party dominated
Senthil et al., 2012 [33]	MC vs. TPC vs. manufacturer and third party joint collection	AHP and TOPSIS	Single vs. dual
Huang et al., 2013 [34]	RC and TC vs. RC	Game theory	Dual, manufacturer-dominated
Hong et al., 2013 [12]	MC and RC vs. MC and TC vs. RC and TC	Game theory	Dual, manufacturer-dominated
Yi et al., 2016 [35]	RC and TC	Game theory	Dual, retailer-dominated

Based on the literature survey, we can figure out that most works focus on the single recycling channel choice puzzle in the manufacturer-dominated CLSC, and apply the game theory to obtain the optimal analytical solution. However, the retailer-dominated CLSC with triple recycling channel, namely, all the OEM, the retailer and the secondary market undertake the collection efforts, which can be observed in the real-world application, has not been well explored yet. In addition, according to the analysis of Savaskan et al. [11], the game theory and the Stackelberg model could provide a quantitative basis for the channel decision. Hence, this paper complements the literature by establishing quantitative models of channel design to investigate how the retailer, which dominates the remanufacturing business in the CLSC, allocates the collection activities in each reverse channel under various circumstances. In addition, we explore the optimal decisions for the retailer to obtain the maximum profit in a retailer-dominated CLSCs with triple recycling channel within the framework of game theory.

3. System Description

Motivated by an actual case of the construction machinery industry in China, we model a retailer-dominated CLSC system with triple recycling channel in this section based on our previous works [35,36]. In this supply chain system, there is an OEM, a retailer (which also acts as the remanufacturer), a secondary market, and end users. The OEM produces the new construction machinery (such as the hydraulic excavator) by using the raw materials, and gathers the worn-out construction machinery through his own service outlets for the remanufacturer. The retailer, which has been given the licence to remanufacture the used products by the Ministry of Industry and Information Technology of China, not only retails the new products for the OEM, but also produces the remanufactured ones. Consequently, the retailer distributes both the brand new construction machinery and the remanufactured one, and signs buy-back contracts with a portion of the customers to reclaim the used products. Motivated by the transfer price mechanism, the secondary market also collects the used construction machinery from the end users for the retailer (remanufacturer). We represent this special supply chain system with a retailer-dominated CLSC model. In this CLSC shown in Figure 1, the retailer is the Stackelberg leader, while the OEM and the secondary market play as the followers. The forward flows are indicated by the solid line, while the reverse flows are represented by the dotted line. It is noteworthy that we only analyse the optimal decisions of the remanufacturer in a single period to make the problem easy to handle, but our model still reflects the real scenario well.

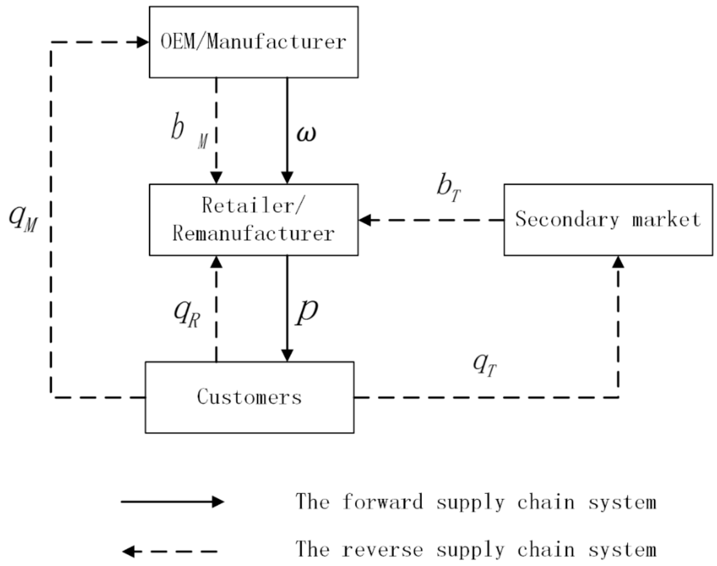

Figure 1. The retailer-dominated system with triple recycling channel.

3.1. Definition of Symbols

The following notations are adopted to develop the mathematical models.

Parameters	Definition
c_m	The cost per unit for producing the brand new product with the raw materials
c_r	The cost per unit for producing the remanufactured product from the returns
p	The unit selling price of the brand new product, then $p = \omega + m$
D	The demand for the products in the market
A	The average recycling cost paid to the end users per used product
A_C	The unit buy-back price afforded to the end users who signs the buy-back contract
R	The reverse logistics cost in the collection activities
C_L	The conversion ratio between the reverse logistics cost and the collection quantities
a	The coefficient characterizes the competition between the OEM and the secondary market in used product collection activities
θ	The conversion ratio between the buy-back price and the collection quantities
π	The profit
Decision Variables	**Definition**
ω	The unit wholesale price
q_M	The amount of used products collected by the OEM
q_T	The amount of used products collected by the secondary market
m	The unit profit of the retailer by selling the brand new product to the customer
D_R	The amount of products remanufactured by the retailer (remanufacturer)
b_M	The transfer price per unit of used product returned from the OEM to the retailer
b_T	The transfer price per unit of used product returned from the secondary market to the retailer

For ease of presentation, let superscripts M, R, T denote the OEM, the remanufacturer/retailer and the secondary market separately. As well, ω and q_M are the decision variables of the OEM, q_T is the decision variable of the secondary market, m, D_R, b_M and b_T are the decision variables of the retailer/remanufacturer.

3.2. Modelling Assumptions

Based on our previous works [30,31], we make the following key assumptions.

1. It is economically feasible to remanufacture, that is, $A + c_r < c_m$, and there is no difference between the remanufactured product and the brand new one. More specifically, $p > \omega > 0$, $b_M > A > 0$, $b_T > A > 0$.
2. There is no market cannibalization between the remanufactured product and the new one, and they have the same functionality though they were identified differently. Herein, the market demand can be characterized as $D = \alpha - \beta(m + \omega)$, $D > D_R$ is set to satisfy the physical constraint. Because the construction machinery has generally long life-cycles, and the market has already achieved the level of saturation, we can hold the view that the variation of demand may be relatively small. In addition, when firms adopt a make-to-order system, the need for the products inventory is reduced [23], and the influence of the inventory cost on the reverse channel choice can be ignored [25]. In order to simplify the computation and guarantee the closed-form solution, we build the model under the deterministic setting and ignore the impact of the inventory cost to follow the vast literature (such as Atasu et al., 2013 [20]; Savaskan et al., 2004 [11]; Shi et al., 2013 [21]) in this field.
3. For the OEM and the secondary market, the collection quantities of one side monotonously increase with the increase of its own reverse logistics cost, while these quantities monotonously increase with the increasing reverse logistics cost of the other side. We further assume that the reverse logistics cost exhibits the diseconomies of scale, as the construction machinery is bulky and hard to be transported. Hence, we formulate the following mathematical relationship:

4. $\begin{cases} C_L q_M^2 = R_M - aR_T \\ C_L q_T^2 = R_T - aR_M \end{cases}$. Herein, a (the competing intensity, $0 \le a < 1$) completely characterizes the recycling competition between the OEM collection and the secondary market collection. Then, the reverse logistics costs of the manufacturer and the secondary market can be written as:
5. $\begin{cases} R_M = \frac{C_L}{1-a^2} q_M^2 + \frac{aC_L}{1-a^2} q_T^2 \\ R_T = \frac{C_L}{1-a^2} q_T^2 + \frac{aC_L}{1-a^2} q_M^2 \end{cases}$. Besides, q_M and q_T are subject to the physical constraint, that is, $q_M + q_T \le D_R$.
6. In this CSLC model, the customers themselves will bear the reverse logistics cost if they sign buy-back contracts with the retailer when they buy the new products. Hence, we further assume that the mathematical relationship between the unit buy-back price A_C paid to the customers who sign the buy-back contract and the number of used products collected by the buy-back contract can be formulated as follows:
7. $A_C = A + \theta q_R (\theta > 0)$, which can be also written as $A_C = A + \theta(D_R - q_M - q_T)$. The parameter θ characterizes the sensitivity of the buy-back price to the collection quantities of the retailer.
8. There exists a Stackelberg game among the OEM, the retailer (remanufacturer) and the secondary market. The retailer acts as the leader to decide the unit profit m through selling the new construction machinery, the total quantities of the remanufactured products D_R, the transfer price b_M paid to the OEM for the collected used products, and the transfer price b_T paid to the secondary market. Then the OEM plays as the follower to decide the wholesale price ω of the new products, and the collection quantities q_M for the retailer. Finally, the secondary market also plays as the follower to decide the collection quantities D_R for the retailer. Figure 2 summarizes the decision process of the game model and the backward induction method to solve it.

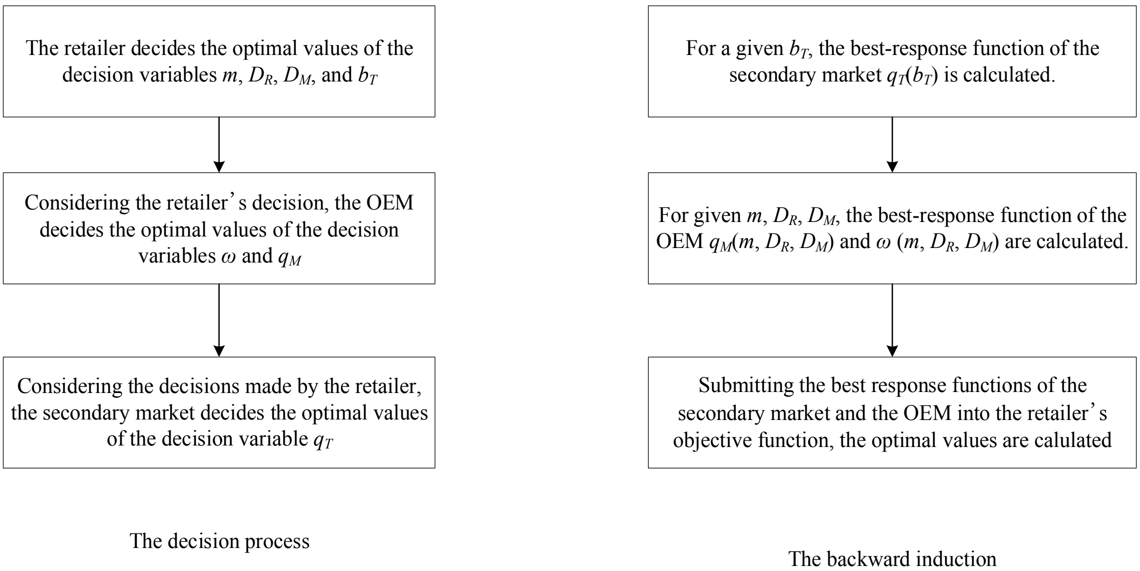

Figure 2. The flowchart of the main methodological steps.

4. Optimal Strategies and Approaches

In this section, we use game theory to analyse the optimal decisions of the members in the system. According to the system description in Section 3, we can formulate the profit functions of the supply chain members as follows:

$$\pi_T = (b_T - A)q_T - \left(\frac{C_L}{1-a^2} q_T^2 + \frac{aC_L}{1-a^2} q_M^2\right), \tag{1}$$

$$\pi_M = (b_M - A)q_M - \left(\frac{C_L}{1-a^2}q_M^2 + \frac{aC_L}{1-a^2}q_T^2\right) + (\omega - c_m)(D - D_R), \quad (2)$$

$$\pi_R = (m + \omega - c_r)D_R + m(D - D_R) - b_M q_M - b_T q_T - [A + \theta(D_R - q_M - q_T)](D_R - q_M - q_T), \quad (3)$$

Then, the optimal decisions of the members in the CLSC can be formulated as follows:

$$\begin{cases} & \max_{m,D_R,b_M,b_T} \pi_R(m, D_R, b_M, b_T; \omega, q_M, q_T) \\ (Retailer): & s.t.(\omega, q_M) = arg \max_{\omega,q_M} \pi_M(\omega, q_M; m, D_R, b_M) \\ & q_T = \arg\max_{q_T} \pi_T(q_T; b_T) \\ (OEM): & \max_{\omega,q_M} \pi_M(\omega, q_M; m, D_R, b_M) \\ (Third\ party): & \max_{q_T} \pi_T(q_T;\ b_T) \end{cases}, \quad (4)$$

By utilizing the backward induction method, we achieve below propositions.

Proposition 1. *In the CLSC model with a triple recycling channel, if* $\alpha - \beta c_m > \left(\frac{1}{\theta} + \frac{1-a^2}{C_L}\right)(c_m - c_r - A)$, *then the optimal number of used products collected from the secondary market, denoted as* ${q_T}^*$, *is*

$$ {q_T}^* = \frac{\frac{1-a^2}{2C_L}\theta\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \quad (5)$$

From Proposition 1, we can firstly conclude that the optimal number of used products collected from the secondary market ${q_T}^*$ monotonously increases with the increase of the conversion ratio C_L. This is because the larger the conversion ratio C_L, the bigger the reverse logistics cost needed to invest in the collection activities. Secondly, ${q_T}^*$ monotonously increases with the increase of the conversion ratio θ, because the larger the conversion ratio θ, the higher the unit buy-back price, and then the remanufacturer may collect more used products from the secondary market. Thirdly, ${q_T}^*$ decreases with the increase of the coefficient a. Since larger coefficient a implies a fiercer competition for the manufacturer and the secondary market in collecting the used products, then less-used products are collected from the secondary market.

Proof. See Appendix A. □

Proposition 2. *In the CLSC model with a triple recycling channel, if* $\alpha - \beta c_m > \left(\frac{1}{\theta} + \frac{1-a^2}{C_L}\right)(c_m - c_r - A)$, *then the optimal number of used products collected by the OEM, and the optimal wholesale prices of the OEM, denoted as* ${q_M}^*$ *and* ω^*, *separately, are*

$$q_M^* = \frac{\frac{1-a^2}{2C_L}\theta\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \quad (6)$$

$$\omega^* = \frac{1}{2}\left[C_m + \frac{\theta(\alpha + \beta c_m) + (c_r + A)\left(1 + \theta\frac{1-a^2}{C_L}\right)}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}\right], \quad (7)$$

Proposition 2 implies that the optimal number of used products collected by the OEM $q_M{}^*$ has the same monotonicity with $q_T{}^*$. Besides, the optimal wholesale prices of the OEM ω^* monotonously increases with the increase of the conversion ratio C_L, θ, and the coefficient a. Because the larger these parameters are, the more cost should be taken to collect the used products, the retailer gains less profit from the remanufacturing business. Consequently, the OEM would accordingly raise the wholesale price.

Proof. See Appendix A. □

Proposition 3. *In the CLSC model with a triple recycling channel, if* $\alpha - \beta c_m > \left(\frac{1}{\theta} + \frac{1-a^2}{C_L}\right)(c_m - c_r - A)$, *then the optimal unit profit of the retailer by selling the new products, denoted as* m^**, the optimal quantities of remanufactured products produced by the retailer (remanufacturer), denoted as* $D_R{}^*$*, the optimal transfer price paid to the OEM, denoted as* $b_M{}^*$*, and the optimal transfer price paid to the secondary market, denoted as* $b_T{}^*$*, are given by*

$$m^* = \frac{\alpha - \beta c_m}{2\beta}, \tag{8}$$

$$D_R{}^* = \frac{\left(1 + \theta\frac{1-a^2}{C_L}\right)\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \tag{9}$$

$$b_M{}^* = \frac{\theta\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)} + A, \tag{10}$$

$$b_T{}^* = \frac{\theta\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)} + A, \tag{11}$$

Hence, the optimal quantities of remanufactured products collected by the retailer in terms of the buy-back contract, denoted as $q_R{}^*$, and the optimal buy-back price paid to the customers who sign the buy-back contract, denoted as $A_C{}^*$, can be calculated by

$$q_R{}^* = \frac{\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \tag{12}$$

$$A_C{}^* = A + \frac{\theta\left[\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)\right]}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \tag{13}$$

Substituting Equations (5), (6) and (11) to π_T yields

$$q_R{}^* = \frac{\frac{\alpha+\beta c_m}{2} - \beta(c_r + A)}{1 + \theta\left(2\beta + \frac{1-a^2}{C_L}\right)}, \tag{14}$$

Substituting Equations (5)–(10) to π_M yields

$$\pi_M{}^* = \frac{(1-a)\left(1-a^2\right)\theta^2}{4C_L}\left[\frac{\frac{\alpha+\beta c_m}{2} - \beta(c_r+A)}{1+\theta\left(2\beta+\frac{1-a^2}{C_L}\right)}\right]^2 + \frac{\beta}{4}\left[\frac{\theta(\alpha-\beta c_m)+\left(1+\theta\frac{1-a^2}{C_L}\right)(c_r+A-c_m)}{1+\theta\left(2\beta+\frac{1-a^2}{C_L}\right)}\right]^2, \tag{15}$$

Substituting Equations (5)–(11) to π_R yields

$$\pi_R{}^* = \frac{\alpha-\beta c_m}{4}\left[\frac{\theta(\alpha-\beta c_m)+\left(1+\theta\frac{1-a^2}{C_L}\right)(c_r+A-c_m)}{1+\theta\left(2\beta+\frac{1-a^2}{C_L}\right)}\right] + \frac{\alpha-\beta(c_r+A)}{2\beta}\frac{\left(1+\theta\frac{1-a^2}{C_L}\right)\left[\frac{\alpha+\beta c_m}{2}-\beta(c_r+A)\right]}{1+\theta\left(2\beta+\frac{1-a^2}{C_L}\right)}, \tag{16}$$

This proposition signifies that the optimal quantities of remanufactured products produced by the retailer $D_R{}^*$ monotonically decrease with the increase of the conversion ratio C_L, θ, and the coefficient a. Moreover, the optimal transfer price paid to the OEM $b_M{}^*$, the optimal transfer price paid to the secondary market $b_T{}^*$, and the optimal buy-back price paid to the customers who sign the buy-back contract $A_C{}^*$, monotonically decrease with the increase of the conversion ratio C_L, θ, and the coefficient a. The larger these parameters are, the more cost should be taken to collect the used products, thus the retailer gains less profit from the remanufacturing business. Consequently, the retailer produces less remanufactured products and has to set higher transfer price and buy-back price to collect more used products. In addition, to elaborately illustrate the effects of these parameters on the number of used products collected by the agents in the CLSC, we conduct a numerical study in the Section 5.

Proof. See Appendix A. □

Corollary. *In the retailer-dominated CLSC with a triple recycling channel, the OEM collection and the secondary market collection make no difference to the retailer, the transfer prices and the collection quantities are all the same.*

This corollary is easy to understand, because the OEM and the secondary market are both faced with the same cost structure in the collection activities, the retailer who also acts as the remanufacturer in the CLSC may provide the same transfer prices to them for the collected used products under the same transfer price mechanism. Hence, the OEM and the secondary market both collect the same number of used products for the retailer.

5. Numerical Study and Discussion

In order to verify the analytical results obtained in the above section and demonstrate the application of the established model, we follow the vast literature (such as Hong et al., 2013; Huang et al., 2013) in this field to conduct a numerical study. We aim to explore the optimal strategies of the remanufacturer on the allocation of the collection efforts to the OEM, the retailer and the secondary market, and analyse the profits of the remanufacturer within the retailer-dominated CLSC with a triple recycling channel for construction machinery remanufacturing.

5.1. Effects of the Reverse Logistics Cost Coefficient on the Collection Efforts Allocation and the Profits of the Retailer

Herein, in order to examine the effects of reverse logistics cost coefficient C_L on the quantities of used construction machinery collected by the members in the system, and on the profits of the retailer, we make assumptions under the following numerical settings. The market size is characterized by $\alpha = 80$, $\beta = 0.2$, $C_m = 25$, the unit processing cost of remanufacturing C_r is medium ($C_r = 10$), the average recycling cost A is medium ($A = 5$), the conversion ratio between the buy-back price and the collection quantities θ is medium ($\theta = 5$), the competition between the OEM and the secondary market in collecting the used products is not very strong ($a = 0.5$), and $C_L \in [0.1, 1]$. Figures 3 and 4 are obtained from numerical simulation in Matlab 2013.

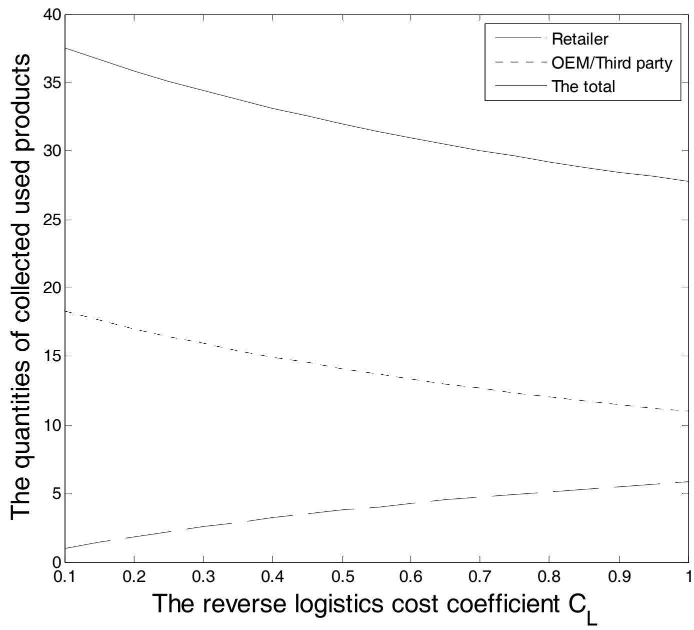

Figure 3. Effects of the reverse logistics cost coefficient C_L on the amount of collected used products.

As shown in Figure 3, the number of used products collected by the OEM and the number of used products collected by the secondary market both drop slowly when the reverse logistics cost coefficient C_L goes up, while the amount of construction machinery collected by the retailer through buy-back contract increases correspondingly. Meanwhile, the total amount of the used construction machinery collected by the agents in CLSC decreases to a certain degree. As well, as illustrated in Figure 4, high reverse logistics cost coefficient C_L makes the profits of the retailer slip precipitously.

Since the parameter C_L characterizes the relationship between the collection quantities, the reverse logistics cost of the OEM and the secondary market in used construction machinery collection activities, a higher value of C_L generally signifies that the OEM and the secondary market should bear more reverse logistics cost to collect the same amount of the used construction machinery. Under circumstances with high reverse logistics cost coefficients, the retailer may choose to collect more used products through signing the buy-back contracts with the customers rather than entrusting the OEM or the secondary market to collect the used construction machinery through the transfer price mechanism. Moreover, higher reverse logistics cost in the used product collection activities leads to higher transfer prices and higher buy-back prices for the returns, the retailer (remanufacturer) should bear more cost. As a result, the profits of the retailer diminish. The managerial significance is that for the purpose of enhancing the profits, the retailer (remanufacturer) should allocate the used product collection activities properly according to the market environment for the OEM and the secondary market to pick-up the used products, and encourage the OEM and the secondary market to optimize the location of recycling facilities, and the vehicle routing arrangements. Furthermore, with the aid of advanced logistics techniques and effective logistics operating systems such as the RFID (Radio Frequency Identification) and Enterprise Resource Planning system, the retailer (remanufacturer) can gain more product returns and profits.

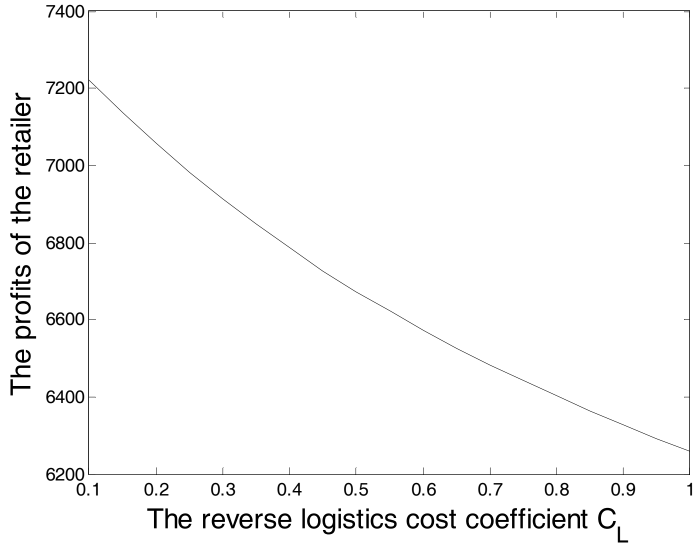

Figure 4. Effects of the reverse logistics cost coefficient C_L on the profits of the retailer.

5.2. Effects of the Competing Coefficient on the Collection Efforts Allocation and the Profits of the Retailer

In this section, aiming to explore the effects of the competing coefficient a on the amount of used construction machinery collected by the OEM, the retailer, and the secondary market in the system, we assume the following numerical settings: $\alpha = 80$; $\beta = 0.2$; $C_m = 25$; $A = 5$; $C_r = 10$; the conversion ratio between the buy-back price and the collection quantities θ is medium ($\theta = 5$); the reverse logistics cost coefficient C_L is large ($C_L = 0.5$), and; $a \in [0, 1)$. Figures 5 and 6 are obtained from numerical simulation in Matlab 2013.

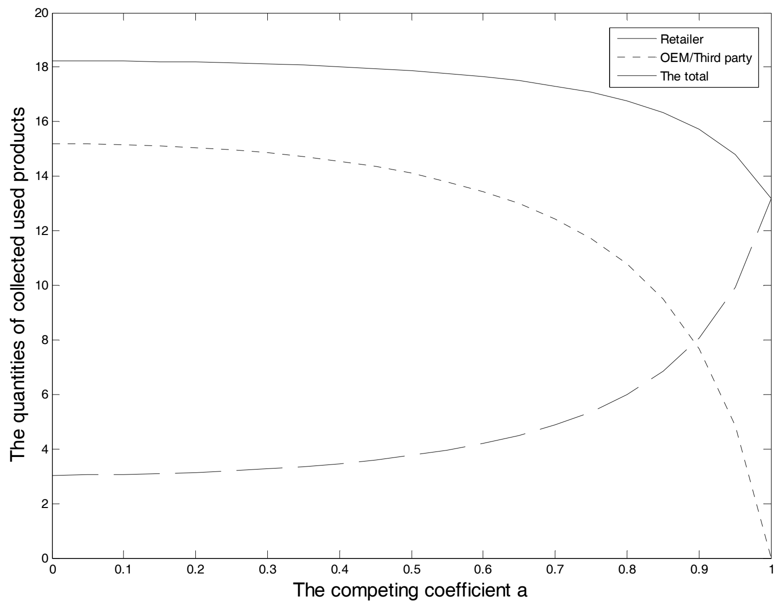

Figure 5. Effects of the competing coefficient a on the amount of collected used products.

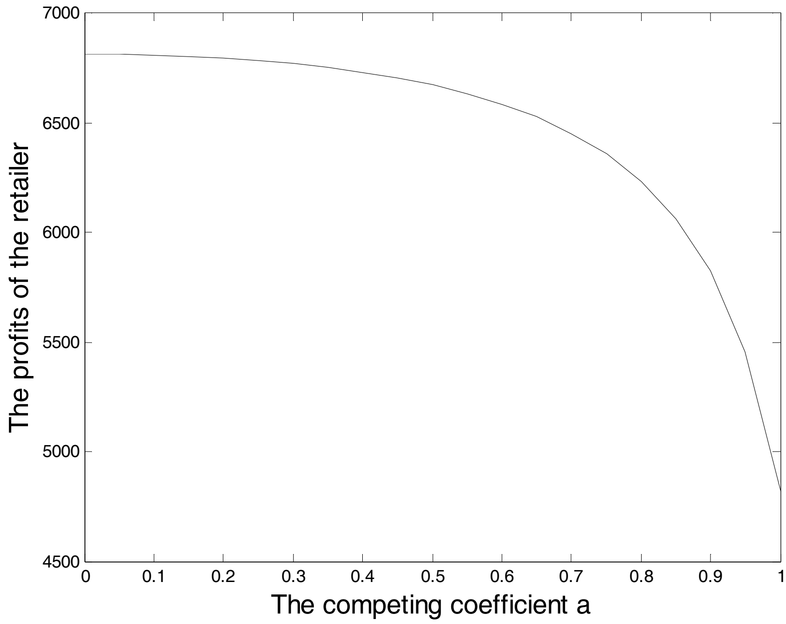

Figure 6. Effects of the competing coefficient a on the profits of the retailer.

As illustrated in Figure 5, when the competing coefficient a goes up, both the number of used products collected by the OEM and the number of used products collected by the secondary market drop sharply, while the number of used products collected by the retailer through buy-back contracts increases correspondingly. At the same time, the total amount of the used construction machinery recycled by the members in CLSC decreases to a certain degree. From Figure 6, we can observe that high competing coefficient a makes the profits of the retailer fall significantly.

The competing coefficient a entirely characterizes the recycling competition between the OEM and the secondary market in the reverse supply chain (Huang et al., 2013) [34]. The larger the competing coefficient a, the more reverse logistic cost the OEM and the secondary market have to spend in collecting the same number of used products. Hence, similarly to the scenario in Section 5.1, the retailer would collect more used products through buy-back contracts, and make the OEM and the secondary market engage in fewer collection activities. Moreover, along with the increase of the competing coefficient a, the retailer would set both high buy-back prices and transfer prices to collect more returns correspondingly. Therefore, it takes more cost for the retailer to remanufacture the returns, and the profit of the retailer decreases. The above analysis implies that the government should adopt macro-control policies to reduce the competing coefficient for the sake of enhancing the development of the remanufacturing industry, and the retailer should balance the collection efforts taken by the members in the retailer-dominated CLSC. As a matter of fact, government grants and the encouragement of cooperation among the OEM, the retailer, and the secondary market on used product collection activities also benefit the supply chain.

5.3. Effects of the Buy-Back Price Coefficient on the Collection Efforts Allocation and the Profits of the Retailer

In this section, we aim to analyze the effects of the buy-back price coefficient θ on the amount of used construction machinery recycled by the OEM, the retailer, and the secondary market in the system and on the profits of the retailer. Herein, we consider the following numerical settings: $\alpha = 80$, $\beta = 0.2$; $C_m = 25$; $A = 5$; $C_r = 10$; the reverse logistics cost coefficient C_L is large ($C_L = 0.5$); the competition between the OEM and the secondary market in collecting the used products is not very strong ($a = 0.5$), and; $\theta \in [0.5, 9.5]$. Figures 6 and 7 are obtained from the numerical simulation in Matlab 2013.

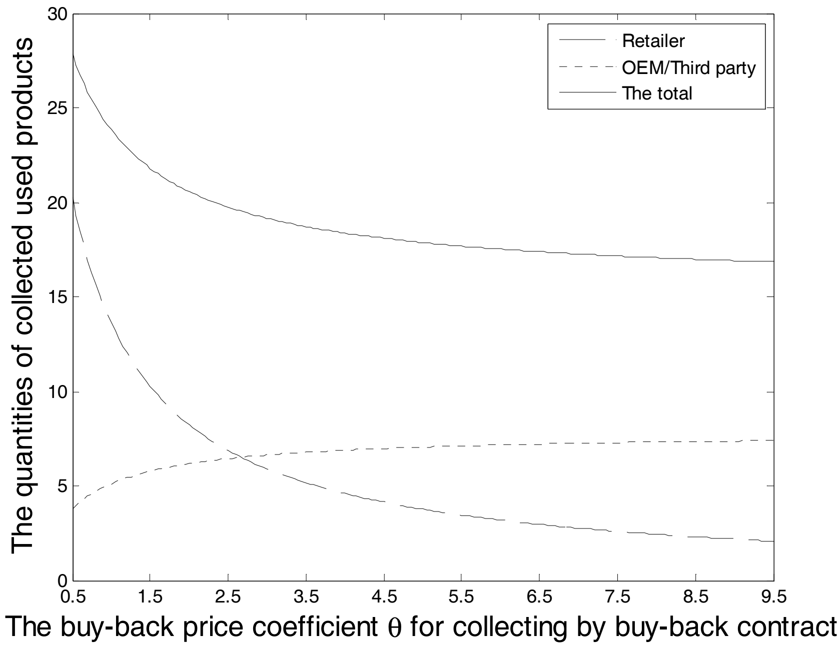

Figure 7. Effects of the buy-back price coefficient θ on the amount of collected used products.

Figure 7 illustrates that both the OEM and the secondary market collect more used construction machinery with the increase of the buy-back price coefficient θ, while the number of used products collected by the retailer through the buy-back contract decreases correspondingly. In addition, the total number of used products collected by the members in the CLSC faces a dramatic decline. As illustrated in Figure 8, the profits of the retailer decrease with the rise of the buy-back price coefficient θ.

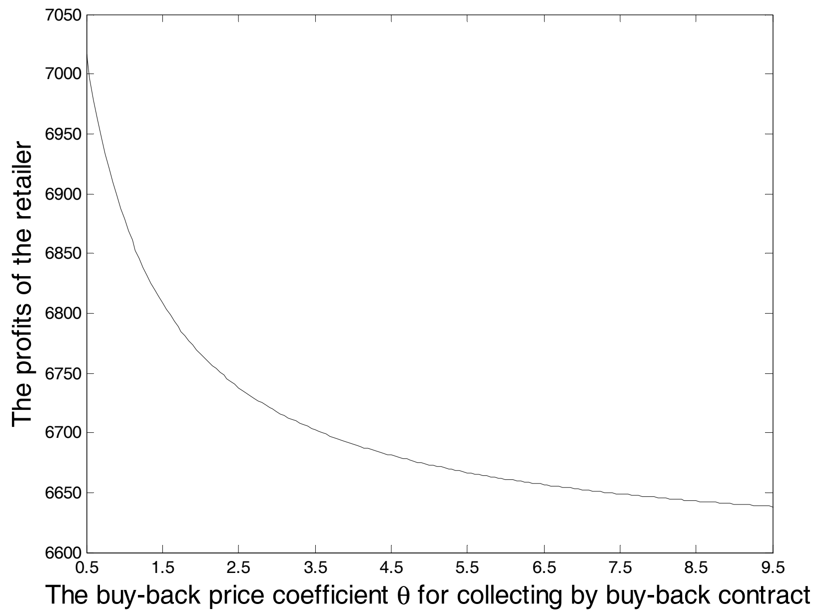

Figure 8. Effects of the buy-back price coefficient θ on the profits of the retailer.

The sensitive parameter θ represents the relationship between the buy-back price and the collection quantities. The larger the value of θ is, the higher the buy-back price must be offered by the retailer for the same number of used products dropped off by the customer. As a result, the retailer may collect more used construction machinery from the OEM and the secondary market through the transfer price incentive mechanism, while collecting fewer used products by signing buy-back contracts with the customers. Similar to the analysis in the above sections, the large value of the buy-back price coefficient θ results in high buy-back price and transfer price. Consequently, the retailer should spend more cost in remanufacturing activities, and the profit of the retailer declines. The managerial significance is that the retailer should appropriately allocate the collection activities to the OEM, the secondary market, and the retailer himself according to the buy-back price coefficient for the sake of gaining more profit. Moreover, offering better after-sales service, trading-in allowance service, providing on-site customer training, and adopting advertising strategies all bring benefits to the retailer. As for the government, to promote the development of the triple recycling channel for the used construction machinery remanufacturing, they can adopt some feasible approaches, such as guidelines on quality assurance and quality information provision, tax subsidies, giving publicity to the use of remanufactured construction equipment, and improve general public environmental awareness.

6. Conclusions

In this paper, we explore strategies for the managers who plan to establish a retailer-dominated CLSC with the OEM, the retailer, and the secondary market all taking part in the collection efforts. Motivated by the examples from construction machinery remanufacturing, we consider a scenario where the retailer is the Stackelberg leader engaged in remanufacturing activities. Based on the framework of game theory, we reveal the key factors which determine the optimal combination mode of the triple recycling channel, and provide management insights for policymaking. On the whole, under the logistic limitation that the number of remanufactured products should not exceed the market demand, the conclusions of this paper can be summarized as:

(1) In a retailer-dominated CLSC with a triple recycling channel, the retailer (remanufacturer) should properly allocate the collection efforts to the OEM, the secondary market and the retailer itself according to the reverse logistics cost coefficient, the competing coefficient, and the buy-back price coefficient;
(2) For the retailer, it is particularly important to reduce the reverse logistics cost coefficient, the competing coefficient, and the buy-back price coefficient in order to drive profits in remanufacturing activities. In addition, we provide policy-making suggestions to the government and offer reference to the companies who aim to engage in construction machinery remanufacturing to handle triple recycling channel puzzles.

However, our research is restricted, and we may conduct further research as follows. One line of inquiry is to consider the channel coordination mechanism in the retailer-dominated CLSC with a triple recycling channel and analyze some special scenarios. The other is to take into account the uncertainty in a CLSC when exploring the optimal strategies for the allocation of used products collection efforts. In addition, other quantitative models and mathematical tools to solve the channel design problem can also be a future research direction.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

There exists a Stackelberg game among the manufacturer and the retailer (remanufacture), and the secondary market. As the leader, the retailer has the first-mover advantage. To study the optimal choices of the supply chain members, we first prove the concavity of the profit functions.

By Equation (1), the first and second order derivatives of π_T to q_T can be calculated by

$$\frac{\partial \pi_T}{\partial q_T} = b_T - A - \frac{2C_L}{1-a^2} q_T, \tag{A1}$$

$$\frac{\partial \pi_T^2}{\partial q_T^2} = -\frac{2C_L}{1-a^2}, \tag{A2}$$

It is obvious that $\frac{\partial \pi_T^2}{\partial q_T^2} < 0$, which implies the concavity of π_T. By setting $\frac{\partial \pi_T}{\partial q_T}$ to zero, the optimal response functions of the secondary market are obtained as follows

$$\hat{q}_T = \frac{1-a^2}{2C_L}(b_T - A), \tag{A3}$$

By Equation (2), the first and second order derivatives of π_M to q_M and ω can be calculated by

$$\frac{\partial \pi_M}{\partial q_M} = b_M - A - \frac{2C_L}{1-a^2} q_M, \tag{A4}$$

$$\frac{\partial \pi_M^2}{\partial q_M^2} = -\frac{2C_L}{1-a^2}, \tag{A5}$$

$$\frac{\partial \pi_M}{\partial \omega} = \alpha - \beta(m+\omega) - D_R - \beta(\omega - c_m), \tag{A6}$$

$$\frac{\partial \pi_M^2}{\partial \omega^2} = -2\beta, \tag{A7}$$

The resulting Hessian matrix of π_M is given by

$$H_{\pi_M} = \begin{bmatrix} -\frac{2C_L}{1-a^2} & 0 \\ 0 & -2\beta \end{bmatrix}, \tag{A8}$$

It is obvious that $|H_{\pi_M}| > 0$, which implies the concavity of π_M. By solving the following equations: $\begin{cases} \frac{\partial \pi_M}{\partial q_M} = 0 \\ \frac{\partial \pi_M}{\partial \omega} = 0 \end{cases}$, the optimal response functions of the manufacturer are obtained as follows

$$\hat{q}_M = \frac{1-a^2}{2C_L}(b_M - A), \tag{A9}$$

$$\hat{\omega} = \frac{1}{2\beta}(\alpha - \beta m - D_R + \beta c_m), \tag{A10}$$

By Equation (3), the first and second order derivatives of π_M to m, D_R, b_M, and b_T can be calculated by

$$\frac{\partial \pi_R}{\partial m} = \frac{\alpha - 2\beta m - \beta c_m}{2}, \tag{A11}$$

$$\frac{\partial {\pi_R}^2}{\partial m^2} = -\beta, \tag{A12}$$

$$\hat{\omega} = \frac{1}{2\beta}(\alpha - \beta m - D_R + \beta c_m), \tag{A13}$$

$$\frac{\partial \pi_R}{\partial D_R} = \frac{\alpha - 2D_R + \beta c_m}{2\beta} - c_r - A - 2\theta\left[D_R - \frac{1-a^2}{2C_L}(b_M - A) - \frac{1-a^2}{2C_L}(b_T - A)\right], \quad \text{(A14)}$$

$$\frac{\partial {\pi_R}^2}{\partial {D_R}^2} = -\frac{1}{\beta} - 2\theta, \quad \text{(A15)}$$

$$\frac{\partial \pi_R}{\partial b_M} = -\frac{1-a^2}{C_L}(b_M - A) + \frac{\theta(1-a^2)}{C_L}\left[D_R - \frac{1-a^2}{2C_L}(b_M - A) - \frac{1-a^2}{2C_L}(b_T - A)\right], \quad \text{(A16)}$$

$$\frac{\partial {\pi_R}^2}{\partial {b_M}^2} = -\frac{1-a^2}{C_L} - \theta\frac{(1-a^2)^2}{2C_L^2}, \quad \text{(A17)}$$

$$\frac{\partial \pi_R}{\partial b_T} = -\frac{1-a^2}{C_L}(b_T - A) + \frac{\theta(1-a^2)}{C_L}\left[D_R - \frac{1-a^2}{2C_L}(b_M - A) - \frac{1-a^2}{2C_L}(b_T - A)\right], \quad \text{(A18)}$$

$$\frac{\partial {\pi_R}^2}{\partial {b_T}^2} = -\frac{1-a^2}{C_L} - \theta\frac{(1-a^2)^2}{2C_L^2}, \quad \text{(A19)}$$

The resulting Hessian matrix of π_R is given by

$$H_{\pi_R} = \begin{bmatrix} -\beta & 0 & 0 & 0 \\ 0 & -\frac{1}{\beta} - 2\theta & \frac{\theta(1-a^2)}{C_L} & \frac{\theta(1-a^2)}{C_L} \\ 0 & \frac{\theta(1-a^2)}{C_L} & -\frac{1-a^2}{C_L} - \theta\frac{(1-a^2)^2}{2C_L^2} & -\theta\frac{(1-a^2)^2}{2C_L^2} \\ 0 & \frac{\theta(1-a^2)}{C_L} & -\theta\frac{(1-a^2)^2}{2C_L^2} & -\frac{1-a^2}{C_L} - \theta\frac{(1-a^2)^2}{2C_L^2} \end{bmatrix} \quad \text{(A20)}$$

The principal minor sequences of the discrimination matrix are $|H_{\pi_R}|_1 = -\beta < 0$, $|H_{\pi_R}|_2 = 1 + 2\beta\theta > 0$, $|H_{\pi_R}|_3 = -\left[\frac{1-a^2}{C_L} + \theta\frac{(1-a^2)^2}{2C_L^2}\right] - 2\beta\theta\frac{1-a^2}{C_L} < 0$, and $|H_{\pi_R}|_4 = -\beta\left[\left(-\frac{1}{\beta} - 2\theta\right)\frac{(1-a^2)^2}{C_L^2} - \frac{1}{\beta}\frac{(1-a^2)^3}{C_L^3}\theta\right] > 0$. This implies that the π_R is a concave function to $(m,\ D_R,\ b_M, b_T)$. By setting $\frac{\partial \pi_R}{\partial m}$, $\frac{\partial \pi_R}{\partial D_R}$, $\frac{\partial \pi_R}{\partial b_M}$, and $\frac{\partial \pi_R}{\partial b_T}$ to zero simultaneously, Equations (8)–(11) can be obtained. Substituting them into $\hat{q}_T$, $\hat{q}_M$, and $\hat{\omega}$, Equations (5)–(7) can be obtained.

Notice that the logistic limitation requiring the number of remanufactured products D_R should not exceed the market demand D, which implies that the condition $\alpha - \beta c_m > \left(\frac{1}{\theta} + \frac{1-a^2}{C_L}\right)(c_m - c_r - A)$ must be satisfied. Throughout this paper, we give tacit consent to satisfaction of the logistic limitation to simplify the analysis. Then Propositions 1 to 3 are proved.

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